Renewable and Sustainable Energy Reviews 14 (2010) 56–72

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

State of the art on high-temperature thermal energy storage for power generation. Part 2—Case studies

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ARTICLE INFO

Article history:
Received 25 June 2009
Accepted 14 July 2009

Keywords:
Solar power plants
High temperature
Thermal energy storage (TES)
Active storage systems
Passive storage systems

ABSTRACT

Power generation systems are attracting a lot of interest from researchers and companies. Storage is becoming a component with high importance to ensure system reliability and economic profitability. A few experiences of storage components have taken place until the moment in solar power plants, most of them as research initiatives. In this paper, real experiences with active storage systems and passive storage systems are compiled, giving detailed information of advantages and disadvantages of each one. Also, a summary of different technologies and materials used in solar power plants with thermal storage systems existing in the world is presented.

Contents

1. Introduction

Solar thermal power plants produce electricity in the same way as other conventional power plants, but using solar radiation as energy input. This energy can be transformed to high-temperature steam, to drive a turbine or a motor engine. Among other system

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doi:10.1016/j.rser.2009.07.036

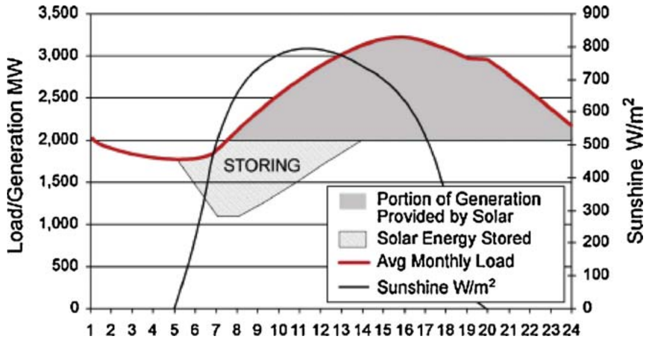

Fig. 1. Sunshine and demand for power [2].

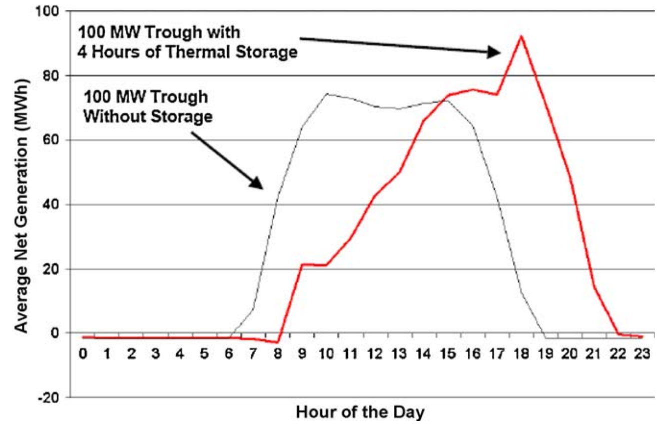

Fig. 2. Results of energy dispatched with and without thermal storge system [2].

parts, storage is a system component which has been neglected, but nowadays its importance within the whole system has attracted the interest of many researchers and companies.

Although thermal energy storage (TES) is used in a wide variety of applications, all the systems are designed to operate on a cyclical basis (usually daily, occasionally seasonally). The systems achieve benefits by fulfilling one or more of the following purposes:

- Increase system reliability, the possibility to reduce the peaks of energy generation means the power plants can work under more stable limits, reducing at same time the probabilities of breakdowns.
- Increase generation capacity [1]: Probably, the most important benefit of the thermal solar energy is the increasing of generation capacity. That means the demand for power is seldom constant over time, and the excess generation available during low demand periods can be used to charge a TES in order to increase the effective generation capacity during high-demand periods. The result is a higher load factor for the plants, helping to generate energy in a stable way.
- Reduction of costs of generation: Energy demands in the commercial, industrial and residential sectors vary on daily, weekly and seasonal bases. These demands can be matched with the help of TES systems that operate synergistically. Energy may be stored in many ways. But in the economy of almost all countries, energy is produced and transferred as heat, the potential for thermal energy storage warrants study in detail, in order to be applied to high-temperature solar power plants.

TES has always been associated closely with solar installations because solar energy availability is limited, and do not coincide with energy demand periods. TES systems have two characteristics of big importance for this application:

- Round-trip efficiency: ratio of the useful energy recovered from the storage system to the amount of energy initially extracted from the heat source.
- They are affected by the laws of thermodynamics and by heat losses in tank, piping and heat exchangers, and by the cost per unit of thermal energy delivery (€/kWh$_{th}$).

Daily, the peak energy consumption takes place after the sunset, as seen in Fig. 1. Storage systems can help to solve part of this problem, dispatching the energy stored during the day in cloudy or night periods (Fig. 2).

Several experiences of TES systems have taken place until the moment in solar power plants. The experiences gathered in these projects were the start point to a new pre-commercial and commercial generation of solar power plants with TES. This paper presents these experiences and compiles the data available in the literature. A previous paper presented the basics of high-temperature thermal energy storage for power generation: concepts, materials, and modelization [3].

2. Thermal energy storage applied to solar power plants

2.1. Experiences of TES in solar power plants

2.1.1. Active direct storage system: direct steam generation

One option for active direct thermal storage is the possibility of generating steam directly in the solar field (Fig. 3), and to use it as heat transfer fluid (HTF) and as storage media. These storage systems are used in process industry to balance demand and generation of steam [4].

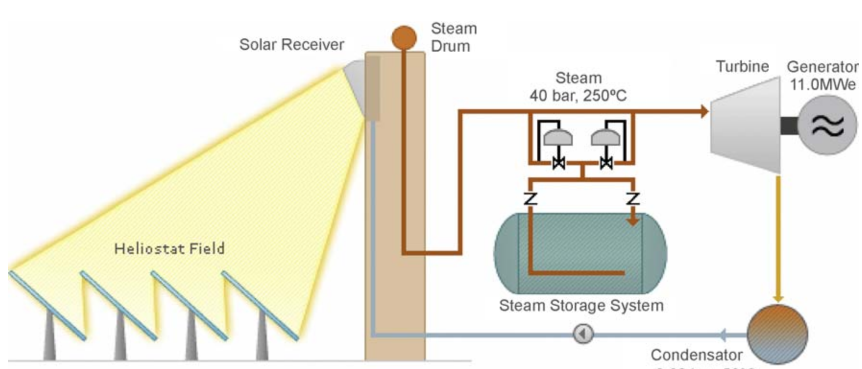

Fig. 3. Scheme of DSG plant installed in PSA [4].

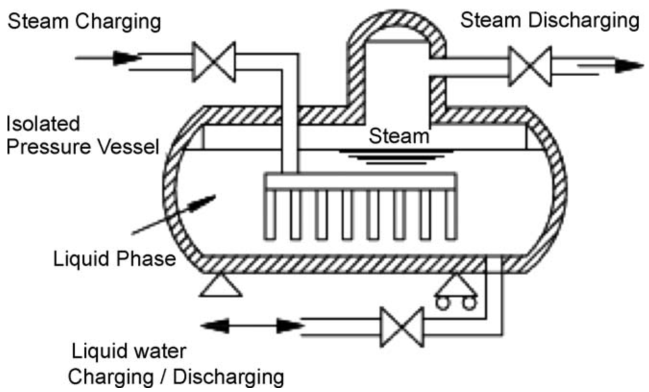

Fig. 4. Scheme of sliding pressure steam accumulator [6].

Steam accumulators are specially suited to meet the requirements for buffer storage in solar steam systems, providing saturated steam at pressures up to 100 bar. They profit from the high volumetric storage capacity of liquid water for sensible heat (up to 1.2 kWh/m^3).

The direct storage of saturated or superheated steam in pressure vessels is not economic due to the low volumetric energy density. Instead, steam accumulators use sensible heat storage in pressurized saturated liquid water.

The introduction of steam accumulators in solar thermal power plants can profit from practical experience gained in operating similar storage systems in fossil fired facilities over decades, and eliminates the need for an intermediate heat transfer fluid and steam-generation heat exchangers. It should also allow the solar field to operate at higher temperatures, resulting in higher power cycle efficiencies and lower fluid pumping parasitics [4].

CIEMAT (Spain) and DLR (German Aerospace Centre, Germany) are currently testing direct steam generation (DSG) at the Plataforma Solar de Almeria in Spain. They are still addressing a number of technical issues. Although there are issues that should be solved, direct steam generation is still one of the most promising opportunities for future cost reductions: fast reaction times and high discharge rates make steam accumulators (Fig. 4) one of the best options for compensation of fast transients in insolation for solar thermal systems using steam as working medium [5].

A steam accumulator can be also charged indirectly. In this case, a heat exchanger is integrated into the liquid volume (Fig. 5). The medium flowing in the heat exchanger cannot be water. In this case, it is possible to use a HTF which works at lower pressure. The system can be considered as buffer storage to direct steam generation solar power plants (DSG power plants).

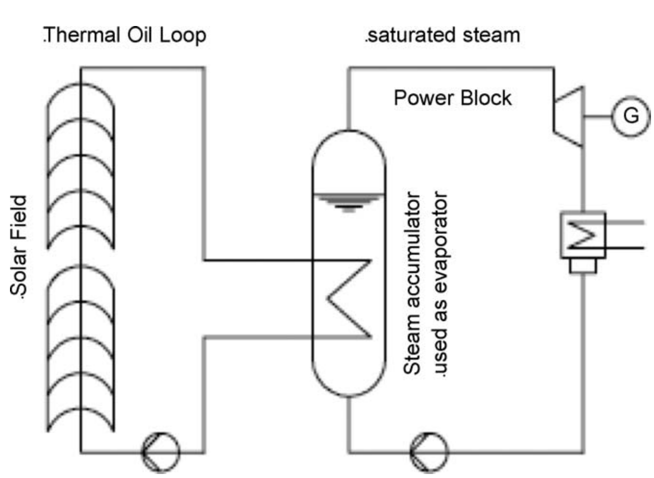

Fig. 5. Scheme of plant using oil heat transfer medium in collectors, with indirect charging of steam accumulator which is also used as heat exchanger [4].

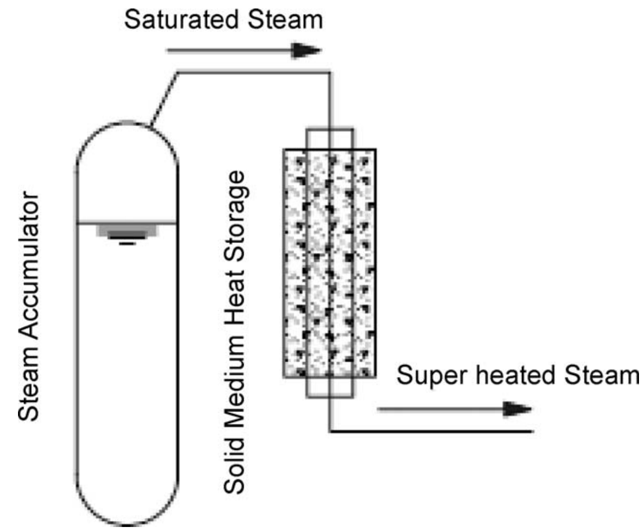

Fig. 6. Steam accumulator with a second storage system, based on sensible storage media [4].

Steam accumulators provide saturated steam. If superheated steam is needed, a second storage system must be connected to the exit of the steam accumulator (Fig. 6).

The most indicated concepts to be used as second storage system are sensible storage media, like concrete or molten salts. In a solar thermal power plant using parabolic troughs only a 10–15% of the thermal energy is needed for superheating steam [7].

In the sliding pressure systems saturated steam leaves the vessel during the discharge process. During the discharge there is a drop in the pressure of the steam. To avoid this, two solutions are presented. First, the application of a separate flash evaporator. In this case, the saturated liquid water from the accumulator is depressurized externally. The cold water is fed into the storage vessel to keep the water level constant. Second, the integration of PCM into the storage vessel to replace partly the liquid water (Fig. 7). Here, the thermal energy associated with the phase change

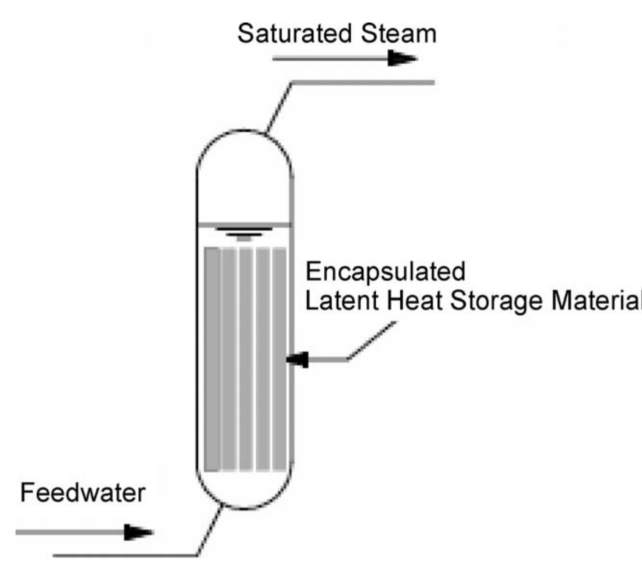

Fig. 7. Steam accumulator with integrated latent heat storage material [4].

is used for isothermal energy storage. PCM usually exhibit a low thermal conductivity so layers of it must be thin to ensure a good heat transfer rate. A solution to fulfil this demand consists in encapsulating PCM in small containers placed inside the vessel. This option of using PCM has two main advantages: on one hand, the thermo-mechanical stress of the vessel resulting from temperature transients is reduced; on the other hand, the characteristic volume-specific storage capacity of PCM is in the range of 100 kWh/m^3, and that helps to reduce the working pressure of the vessel, compared to working with steam storage.

2.1.2. Active direct storage system: direct steam storage (experience of PS10)

The company Abengoa Solar NT is promoting in Seville since 1999 the installation of the PS10 solar power plant. This project, with participation of CIEMAT on sizing and optimization of design of solar parts, uses the technology of volumetric air receiver and a TES system based on a dual system, storing saturated steam in a ceramic alumina bed. PS10 is situated in the limits of Sanlúcar la Mayor, near to Seville, Spain.

This plant was built to operate a central receiver solar power plant in a commercial basis, in the range of 10 MW, producing electricity in a grid-connected mode. This project started ten years later from the last research initiative in the development of solar tower technology, the erection of Solar Two, in 1994 (Figs. 8 and 9).

The scheme of PS10 solar plant, based in scheme of PHOEBUS solar plant, is shown in Fig. 3 [4]. PHOEBUS was a pilot experimental plant operated between 1993 and 1995 with the aim to test the feasibility of a volumetric air receiver system concept. During full-load operation of the PS10 plant, part of steam produced at 250 °C and 40 bar is employed to load the thermal storage system. For cloudy transient periods, the plant has a saturated water thermal storage system, with a thermal capacity of 20 MWh, equivalent to an effective operational capacity of 50 min at 50% turbine workload [9]. The storage system, shown in Fig. 13 [8,9], is composed by four tanks that are sequentially operated in relation to their charge status. These storage tanks can store about 12 MWh$_{th}$.

Fig. 8. The four thermal storage tanks of PS10 solar plant [9].

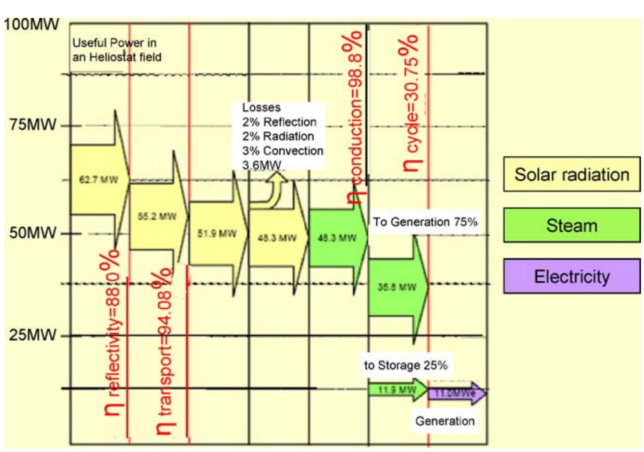

Fig. 9. Scheme of energetic balance in PS10, with a 25% of thermal energy storage [9].

In this case, the average efficiency from solar energy to electricity of the plant is about 17.5%, with a storage efficiency of about 92.4%. Fig. 14 shows the energetic efficiency of every step of the energy production process in PS10 solar plant [9].

In order to cover sunless periods, PS10 solar plant includes a unit of steam generation powered by natural gas, with capacity to reach a 15% of total plant production.

2.1.3. Active direct storage system: experience at Solar One (thermocline)

Solar One power plant was the first test of a large-scale thermal solar power tower plant. Solar One was designed by the Department of Energy (DOE), Southern California Edison, LA Dept of Water and Power, and California Energy Commission. It was located in Daggett, CA, about 10 miles (16 km) east of Barstow. It operated from 1982 to 1988.

This solar plant was provided with a central receiver system. It incorporated a thermal storage system that could be used to buffer the effects of clouds, and avoid interruptions of electricity supply to the grid. This TES was based on a one tank thermocline storage concept [10,11], and consisted in a one tank filled with rocks and sand, using oil as the HTF. Several banks of exchangers allowed the heat to pass between the oil/rock storage tank and the steam cycles used in the receiver and turbine. The TES system extended the electrical production capability into the night.

The project met most of its technical objectives by demonstrating the feasibility of generating power at 10 MWe for eight hours a day near to summer solstice and four hours a day near to winter solstice. The average efficiency from solar energy to electricity of the plant was about 16% [12].

2.1.4. Active direct storage system: experience of SEGS I (two tanks with oil)

Solar Energy Generating Systems (SEGS) is the name given to nine solar power plants in the Mojave Desert in California. These plants have a combined capacity of 354 megawatts (MW) making them the largest solar power installation in the world. The plants were built between 1984 and 1991 by the company Luz Industries (Israel).

The SEGS I plant included a direct two-tank storage system with 3 h of full-load storage capacity [13]. In this plant, a mineral oil called Caloria, specifically designed for this application, was used as HTF and as storage material. This oil was stored in two different tanks: a hot tank, where the oil was stored after being heated in the solar field, to a temperature of 307 °C, and a cold tank, where the oil was stored at 240 °C after discharging its energy over the power block.

Because power plants moved to higher operating temperatures to improve power cycle efficiency, they also switched to a new higher temperature heat transfer fluid. Unfortunately, this fluid has a high vapour pressure, and it cannot be used in the same type of large non-pressurized storage tank system similar to the one used for SEGS I. Pressurized tanks are very expensive, and they cannot be manufactured in large sizes.

The Caloria oil represented 42% of the investment cost. This was the reason why a storage system similar to the SEGS I storage concept was not repeated in later SEGS plants.

The main advantage of this storage technology is that the same fluid is used as HTF and as storage material. Compared to the next technology used, in the Solar Two plant, the intermediate heat exchanger (oil-to-salt) is not needed, which means a cost reduction of the power plant. The main disadvantage is the high quantity of oil required into storage tanks, increasing the cost of installation. Furthermore, pressurized tanks needed for the storage fluid (oil) imply a high cost due to its high vapour pressure.

2.1.5. Active direct storage system: experience at Solar Two (two tanks with molten salts)

In 1995 Solar One was converted into Solar Two, by adding a second ring of 108 larger 95 m^2 (1000 ft^2) heliostats around the existing Solar One, totaling 1926 heliostats with a total area of 82,750 m^2 (891,000 ft^2).

At Solar Two the use of molten salts was found to be a solution to the problems of the storage system of Solar One. A consortium of enterprises led by Southern California Edison joined with US Department of Energy (DOE) retrofitted the solar One [14]. Solar Two was decommissioned in 1999, and was converted by the University of California, Davis, into an Air Cherenkov Telescope in 2001.

The thermal energy storage tanks of Solar One plant were demolished, and two new tanks for a molten salt energy storage system were built by Pitt-Des Moins enterprise. Each tank was sized to store the entire salt inventory. The thermal energy storage system was designed to deliver thermal energy at full-rated duty of the steam generator for three hours at the rated hot and cold salt temperatures of 565 and 290 °C. The total capacity storage of the plant was 105 MWh_{th}, that means 35 MW capacity [15]. The average efficiency from solar energy to electricity was about 19%.

The improvement of efficiency of SEGS plants meant higher solar field temperatures, around 400 °C. The mineral oil used in SEGS I is very flammable, being the main handicap to use it as HTF in new plants like Solar Two. On the other side, the use of synthetic oils dramatically increases the cost of HTF storage system, so it was necessary to develop and evaluate the feasibility of other kind of installation configurations and storage materials. In Solar Two, the chosen thermal energy storage media was molten salt, composed of a mixture of 60% of sodium nitrate ($NaNO_3$) and 40% of potassium nitrate (KNO_3). This mixture melted at 207 °C, was thermally stable to about 600 °C, and offered a favourable combination of high density, low vapour pressure, moderate specific heat, low chemical reactivity, and low cost.

An impurity was discovered – magnesium nitrate, $Mg(NO_3)_2$ – which added complexity to the melting process (due to that the salts are not pure but commercial salts). The impurity decomposed rapidly when the salt was heated above 480 °C. After the initial melt, the salt inventory was heated to 540 °C and held at that temperature for 20 days to reduce the levels of impurity. Over the course of the project, the melting point of the salt gradually lowered from 207 to 202 °C. This change appeared to have no effect on the performance of the plant.

The composition of the salt changed throughout the project. After the initial melting and thermal conditioning of the salt, perchlorate (ClO_4^-) due to impurities on the salt decreased, magnesium stayed low and nitrite was formed within the bounds of equilibrium expectations. But no problems were observed with these changes [15].

The storage system of Solar Two plant consisted in two tanks flat-bottom, domed-roof, cylindrical, atmospheric tanks. The cold tank was fabricated from carbon steel, and the hot tank, from stainless steel (Fig. 10). In order to monitor the level into the tank, each tank was equipped with bubbler level detectors [16].

The cold tank contained two active 25 kWe immersion heaters and one spare that maintained the tank at 290 °C when solar radiation was not enough, in order to avoid the molten salt temperature decrease under the melting point. The sides and roof of the tank were insulated respectively with 23 and 15 cm of mineral wool blankets overlaid with 5 cm of fibreglass boards. The exterior of the tank was covered with aluminium jackets for weather protection, and the bottom of the cold tank was insulated with 41 cm of foam glass insulation under 10.2 m of the 11.4 m of diameter of the tank [17].

The hot tank contained three active 25 kW_e immersion heaters and one spare that maintained the tank at 565 °C, in order to be able to keep generating power when solar radiation was not enough. The sides and roof of the tank were insulated with 46 and 30 cm, respectively, of mineral wool blankets overlaid with 5 cm of fibreglass boards. The exterior was covered with an aluminium jacket for weather protection. The bottom of the tank was insulated with 15 cm of insulating firebrick on top of 30 cm of foam glass insulation under 10.2 m of the 11.4 m of diameter of the tank. This plant has round-trip energy storage efficiencies of 97%.

An optimization of the thermal storage system involves the assessment of numerous parameters [18], including the inverse relationship between the surface area and cost of oil heat exchanger, and the quantity and cost of the storage inventory; and the inverse relationship between the surface area of the oil-to-salt heat exchanger and the part of load performance penalty of the Rankine cycle when operating from thermal storage.

In an effort to reduce heat losses as the tanks were charged or discharged, piping was connected to the vents of the two tanks so that air in the ullage space would not exchange with ambient air. This air will be conduced from the filled tank to the empty tank.

Heat losses were measured once the vessel was at the steady state, and results showed that the thermal losses are basically a fixed value to the environment. Table 1 shows the values of the losses in Solar Two plant.

The two-tank system implemented in this test is a relatively low-risk approach. No barriers to future implementation were

Fig. 10. View of two-tank storage system of Solar Two thermosolar plant: cold tank (left) and hot tank (right) [15].

Table 1
Values of thermal losses in tanks and sumps, in every component, calculated and measured, of Solar Two plant [15].

Major Equipment	Calculated Thermal Loss [kW]	Measured Thermal Loss [kW]
Hot tank	98	102
Cold tank	45	44
Steam generator sump	14	29
Receiver sump	13	9.5

evident [14]. This experimental plant reached to demonstrate dispatching energy several times, and the production of a constant output of electricity at night and through clouds.

2.1.6. Active direct storage system: experience at Solar Tres (two tanks with molten salts)

Placed on Fuentes de Andalucia, near to Seville (Spain), Solar Tres power plant is the first commercial solar plant with central receiver and uses Solar One and Solar Two's technology for commercial electrical production of 15 MW. A large molten nitrate salt storage tank is used giving the plant the ability to store 600 MWh, a storage system with 15 h of storage (Fig. 11). That means that this plant can operate around 6500 h every year. This plant was built in 2008 [18].

The thermal storage system, using molten salts as storage media (a mixture of $NaNO_3$ and KNO_3), is based on two tanks direct technology. That means that the plant uses the same fluid as a working fluid that allows for collection, transport and storage of the thermal energy with also very high efficiencies through the high top and differential temperatures.

The hot tank stores the molten salts at about 565 °C, and was made in ASTM A 240 Grade 347 stainless steel. The cold tank, made in ASTM A 516 Grade 70 carbon steel, stores the molten salts at about 288 °C. The capacity of storage was 588 MWh_{th}. The large thermal storage capacity for very high utilization factors of the plant is above 70%.

2.1.7. Active indirect system: experience of Andasol I

Andasol I is a Sener solar thermal power plant, with a solar field based on parabolic trough technology. It is located in Guadix, Granada (Spain). In the parabolic troughs the HTF is superheated steam. Steam of the solar field passes its energy, thanks to a heat exchanger, to the storage media, molten salts (40% $NaNO_3$ and 60% KNO_3, also called solar salt, with a melting temperature about 221 °C). The storage system is based on two tanks indirect system, with working temperatures of 291 °C in the cold tank and 384 °C in the hot tank.

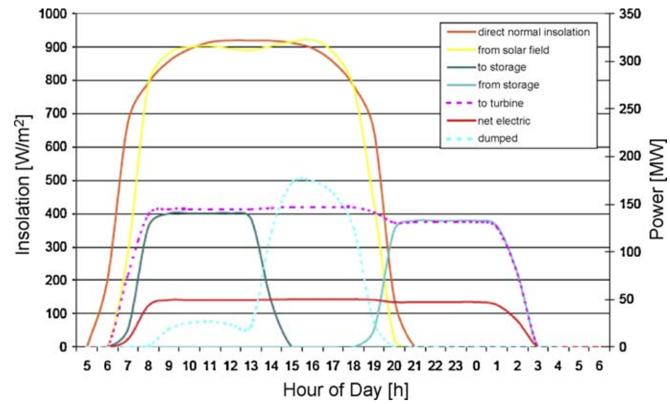

Fig. 12. Insolation and power curves of AndaSol I thermosolar plant [13].

The storage capacity of the Andasol I solar plant is about 1010 MWh_{th}, that means about 7.5 h of full-load production of electricity. The annual average efficiency converting from solar energy to electricity is 14.7% [19].

According to Spanish laws, Andasol I includes the possibility to produce a 15% of electricity with natural gas, in order to overcome the cloudy periods.

In Fig. 12 it is possible to see, for a typical summer day, the curves that characterise the solar plant daily work cycle: the curve of insulation and the curves of power from solar field, to storage and net electricity production, mainly. It is interesting to remark that there is a non-obvious quantity of energy dumped after the storage system is completely charged [13].

2.1.8. Active indirect storage system: Luz proposal of Cascade Latent Heat Storage (CLHS)

In this case, different PCM were tested, in different storage modules. A theoretical analysis of a simplified model of this new plant [20], presented that for a single charging/discharging processes, Cascade Latent Heat Storage yields exergetic advantages

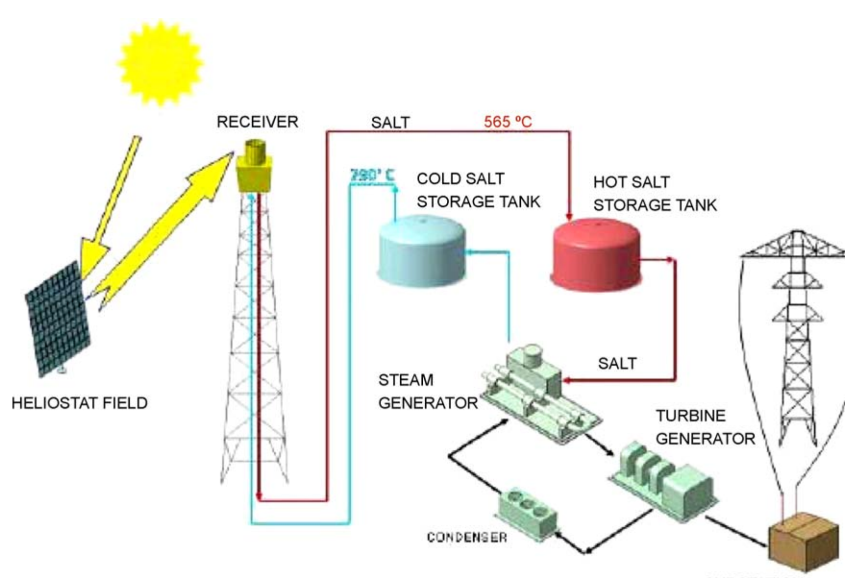

Fig. 11. Scheme of Solar Tres power plant [18].

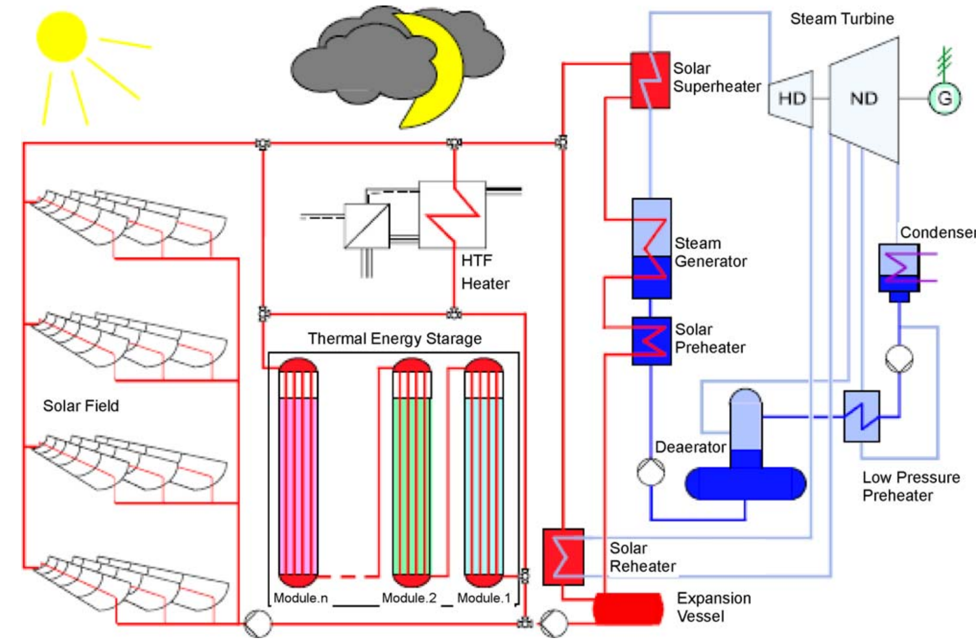

Fig. 13. Scheme of installation of a parabolic through power plant, with PCM-storage system [23].

if operated in counter-flow. A numerical one-dimension model of packed bed type CHLS was validated with experimental results [21].

A new study [22] affirms the positive effect of a CLHS compared to a non-cascaded Latent Heat Storage (LHS) with respect to a higher utilization of the possible phase change, and a more uniform outlet temperature on time. And more, the inlet temperature of HTF and its flow has a strong relation, and the results are better in CLHS. Fig. 13 shows a scheme of the installation. This thermal energy storage concept was designed for solar power plants which included parabolic trough technology in their solar fields. But with a right selection of the PCM, it is possible to transfer this technology to central receiver solar plants.

Compared to non-cascaded LHS, CLHS allows a higher portion of the PCM to run through the phase change material during a charging/discharging cycle (Fig. 14). In addition, a CLHS shows a more uniform heat transfer oil outlet temperature during discharging the non-cascaded LHS. About 92% of the PCM in CLHS was totally molten at the end of charging, and about 67% was completely solid at the end of discharging. Therefore, with multiple consecutive charging/discharging cycles several phase boundaries can occur, if discharging begins before the annular segments PCM was totally molten.

On the other hand, results of other studies [25] indicate that in the charging process natural convection has a dominant role, after a brief initial period of conduction dominating heat transfer.

If a comparison between CLHS and molten salt two-tank storage system is done, the conclusions are [22]:

- Using less quantity of salt, CLHS achieves the same storage capacity than two-tank system.
- A heat exchanger is necessary with CLHS, and HTF outlet temperatures would not be as uniform as at a molten salt two-tank storage system.
- Tanks storage system needs two additional pumps for molten salts, and also some heat tracing to keep the salt liquid, what a CLHS would not need.

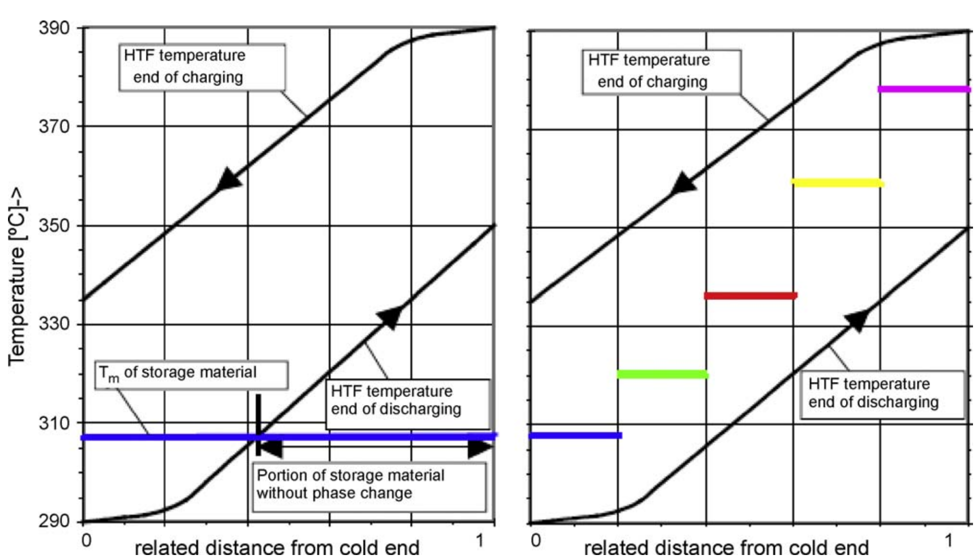

Fig. 14. Behaviour differences between one PCM-storage system and a 5 PCM-storage system with staged melting temperatures [24].

Fig. 15. View of high-temperature concrete storage system [29].

Although the technical feasibility of the CLHS system has been proven, further development of the concept was hindered because of: the thermodynamic penalty of going from sensible heat to latent heat and back to sensible heat; the complexity of the system; and the uncertainty over the lifetime of PCM.

In conclusion it is possible to affirm with CLHS there is a higher utilization of PCM-storage capacities, and more uniform outlet temperature over time. On the other side, this system means a heavy increase of cost, due to a higher number of storage tanks, and a higher quantity of heat transfer fluid and PCM. And more, further PCM needs to be identified which also offers a sufficient heat of fusion and a satisfying corrosiveness.

2.1.9. Passive storage system: Plataforma Solar de Almeria experience (Concrete)

Solid media sensible storage systems are tested by DLR in Plataforma Solar de Almería. Solid media sensible heat storage units have been developed in the project WESPE [26,27], funded by the German Government from December 2001 until December 2003, and storage temperatures of 325 °C have been reached. The focus of this project laid on the development of an efficient and cheap sensible storage material, on the optimization of the tube register heat exchanger and on the demonstration of this technology with a 350 kWh test unit.

In a solid media storage the heat exchanger for the heat transfer fluid is embedded in a solid matrix [28] (see Fig. 15). The thermo-physical properties of the solid storage materials, such as density ρ, specific heat capacity cp, thermal conductivity λ, coefficient of thermal expansion (CTE) and cycling stability as well as availability, costs and production methods are of great relevance. A high heat capacity (ρ^*cp) reduces the storage volume and a high thermal conductivity λ increases the dynamic in the system. The CTE of the storage material should fit to the CTE of the material of the embedded metallic heat exchanger. A high cycling stability is important for a long lifetime of the storage. With respect to these techno-economic aspects, high-temperature resistant concrete as developed for parabolic trough power plants is proposed as suitable solid storage material [28].

Two different storage materials have been developed in parallel [30], as an innovative storage material a castable ceramic and alternatively, a high-temperature concrete. Both developed materials are principally composed of a binder system, aggregates and a small amount of auxiliary materials.

The castable ceramic is based on a binder including Al_2O_3. The binder is set chemically under ambient conditions and forms a solid, stable matrix, which encloses the aggregates. As main aggregate iron oxides, accumulated as waste material in strip steel production, is used. Auxiliary materials are needed to improve the handling of the ready mixed material, for example as accelerator or for reduction of viscosity.

For the high-temperature concrete blast furnace cement is used as binder, again iron oxides are used as main aggregate, as well as flue ash and again a small amount of auxiliary materials.

The material properties have been analyzed at DLR. Shear stress analysis has proven that the contact between tubes and the solid is very good at ambient temperature as well as at elevated temperatures until 350 °C, even after 160 thermal cycles.

In an overall view high-temperature concrete seems to be the most favourable material. Reasons are the lower costs, higher strength of the material and easier handling of the ready mixed

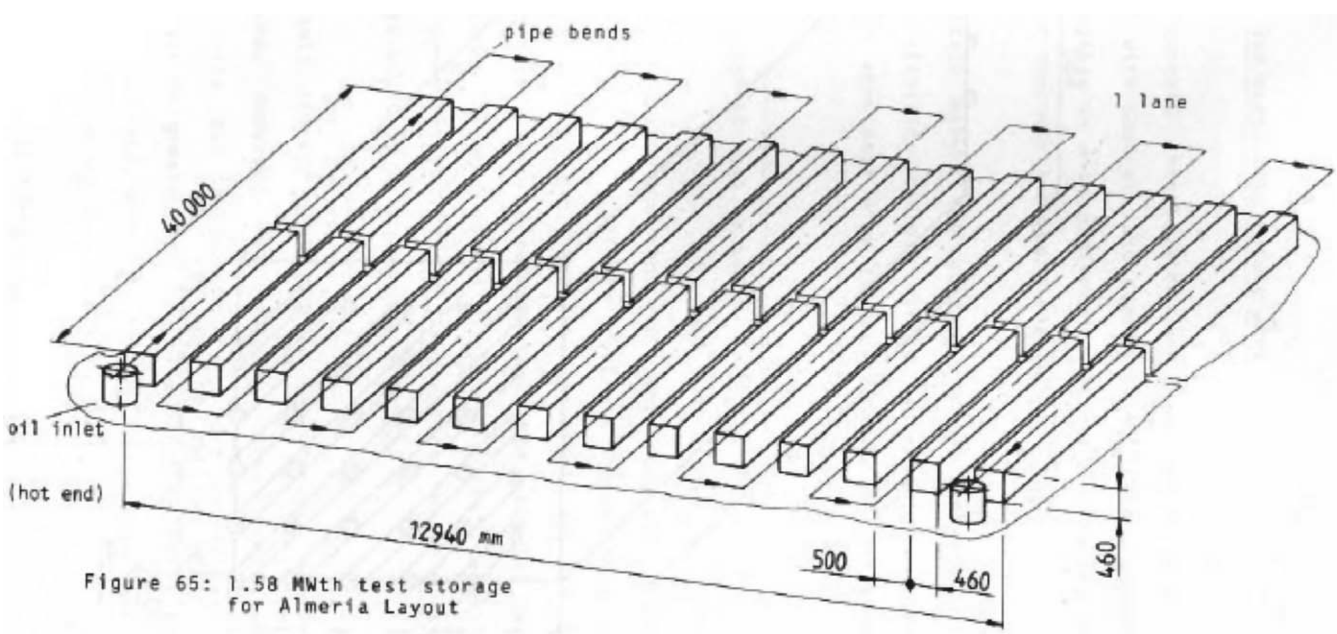

Fig. 16. Scheme of storage test plant in PSA [31].

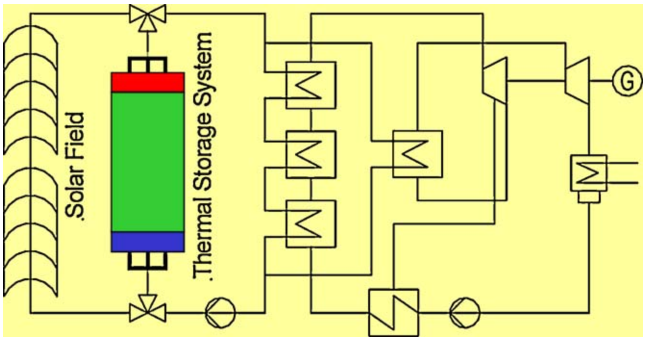

Fig. 17. Scheme of the solar energy storage system proposed by DLR–ZSW [31].

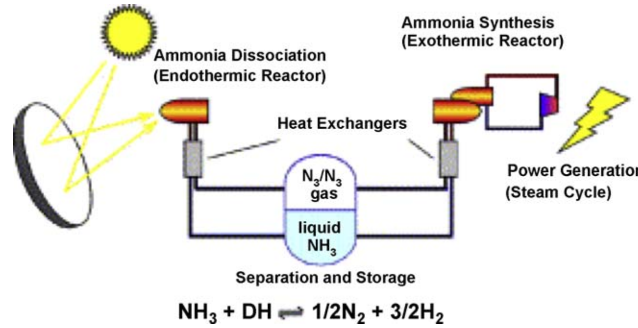

Fig. 18. Scheme of installation of a parabolic through power plant, with chemical storage system [23].

material. However, the further development of cracks in the test modules needs to be investigated, when cycling at operation temperature has been demonstrated. On the other side castable ceramics has a 20% higher storage capacity and 35% higher thermal conductivity and still some potential for cost reduction.

Between 1991 and 1994, two concrete storage modules were tested at the storage test facility at the Centre for Solar Energy and Hydrogen Research (ZSW), a research centre belonging to DLR, in Stuttgart. ZSW in collaboration with the companies ZUEBLIN and FLAGSOL examined during the period 2001–2006 the performance, durability and cost of using solid thermal energy storage media in parabolic trough power plants. The system uses the standard HTF in the solar field, which transfers its heat through an array of pipes system, imbedded in the solid storage media (Fig. 15).

The main advantage of this approach is the low cost of the material, including a good contact between the concrete and piping, and the heat transfer rates into and out of the solid medium.

These tests took place in the Plataforma Solar de Almeria (PSA) in Southern of Spain during 2001–2006. DLR performed initial testing and found that both castable ceramic and high-temperature concrete were suitable for solid media, sensible heat storage systems. However, the high-temperature concrete is favoured because its lower costs, higher material strength and easier handling (Fig. 16). Moreover, there is no sign of degradation between the heat exchanger pipes and storage material [32].

Because of the modular nature of concrete storage, DLR has identified approaches that allow the storage system to better integrate with the solar fields and power cycle. DLR is also testing a new more optimized concrete storage module at the University of Stuttgart [33].

A new test experience was done in 2004 at the Plataforma Solar de Almeria. The thermal energy was provided by a parabolic trough loop with a maximum thermal power of 480 kW. Temperatures of storage reached were about 390 °C, with a range of 340–390 °C. The storage capacity for the ceramic storage unit is around 350 kWh, and the HTF was mineral oil.

Two different storage materials were developed in this experience, castable ceramic (an innovative storage material, based on a binder containing Al_2O_3) and a high-temperature concrete. A tubular heat exchanger is integrated into the storage material. That means an increasing of costs of heat exchanger, and in engineering.

Some conclusions of the experience were that both materials (concrete and castable ceramic) are suitable to use as a solid media

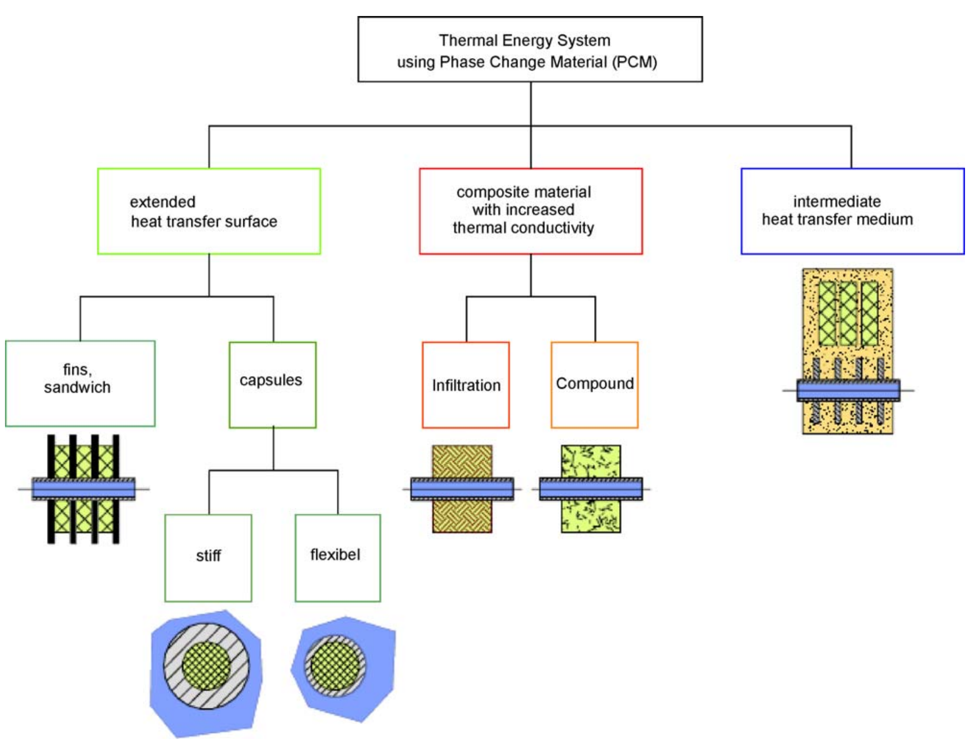

Fig. 19. Classification of PCM-storage concepts investigated in the DISTOR project [38].

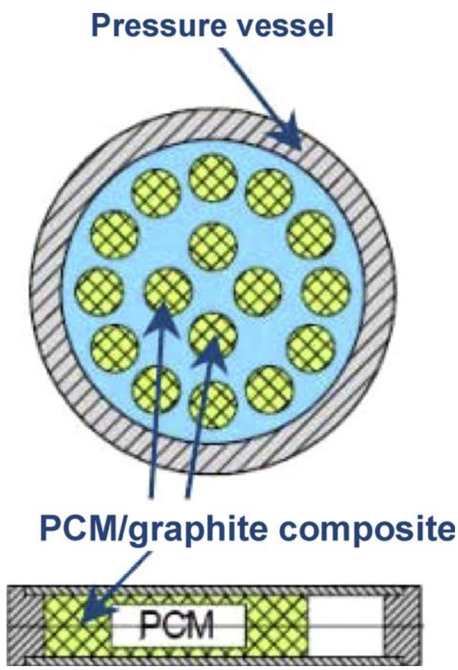

Fig. 20. Internal arrangement of PCM/graphite composite (source: DLR Stuttgart).

heat storage system. However, considering the results, high-temperature concrete seems a better solution, mainly due to its lower cost, higher material strength and facility to handling. The effects of thermal load on concrete in the case of using water as HTF was studied by Cerny et al. [34]. There was no degradation of heat transfer between the heat exchanger and storage material, after approximately 60 cycles.

On the other side, castable ceramics have a storage capacity 20% higher and a thermal conductivity 35% higher than the high-temperature concrete, and a good potential for cost reduction as well [10,35,36].

Tube register design was found to be the best because heat transfer enhancement is important, the material to be used is concrete with quartz aggregates, and fins and other structures are not cost effective.

2.1.10. Passive storage media: combination of sensible and latent storage

The last mechanism of storage is the result of a combination of latent heat storage and sensible heat storage systems, as the one proposed by DLR–ZSW for solar plants [31] (hybrid system storage, shown in Fig. 17). This prototype was called hybrid storage system.

The first prototype of hybrid storage system, made in DLR Stuttgart in 1993, was of 200 MWh_t of capacity, and was designed for about 3 h of charging and 1 h of discharging process. The HTF used was synthetic oil, and three storage materials were used: sodium nitrate ($NaNO_3$, with melting temperature of 310 °C), concrete, and a mixture of NaOH/NaCl (with a melting point of 370 °C).

The most innovative aspects of this concept was the possibility to improve the efficiency of the storage systems, due to the combination of good thermal conductivity and reduced price of concrete with a good storage characteristics of PCM.

2.1.11. Chemical storage: Australian National University pilot plant

Based on the concept schematised below, the Australian National University (ANU) is experimenting with a solar driven closed-loop system, operating on a paraboloidal dish concentrator (Fig. 18) [23].

The experience developed by ANU consists in a dish of around 20 m^2 of 15 kW_{sol} receiver reactor. The storage concept (Fig. 18) includes a fixed inventory of reactants passing alternately between energy storing and energy releasing reactors with provision for ambient temperature storage of reactants in between. These reactors are packed bed catalytic units which use standard commercial catalyst materials.

With this experience, ANU demonstrates the feasibility of this technology, and the possibility to apply it in trough solar plants. In addition, the use of ammonia like a solar thermal storage system has distinct advantages.

The advantages of this system are that unwanted side reactions are not possible, making solar reactors very easy to control, the endothermic reaction takes place at temperatures well suited to solar concentrators [23], automatic phase separation of ammonia and hydrogen/nitrogen is provided, a common storage tank can be used and there is around 100 years of industrial experience with the Harber-Bosch process.

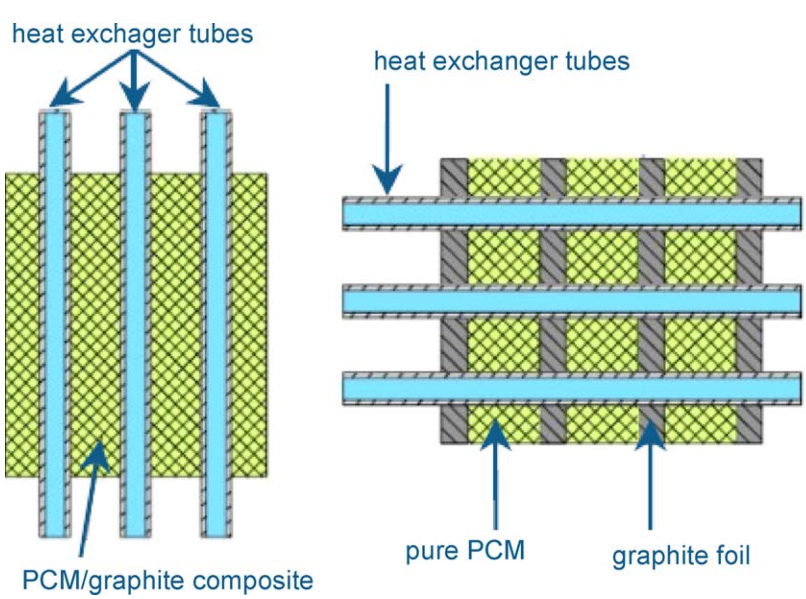

Fig. 21. External arrangement of PCM/graphite composite (source: DLR Stuttgart).

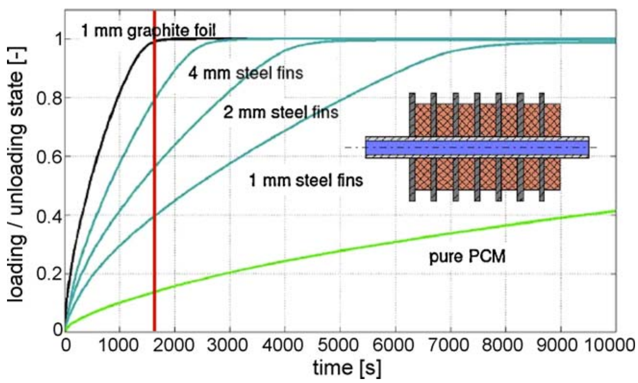

Fig. 22. Experimental results of charging and discharging for configurations with different thickness steel fins, and with graphite foils (source: DLR Stuttgart).

2.2. Other proposals

2.2.1. Innovate long term approaches using latent heat materials

In order to improve and overcome the disadvantages of each of the technologies described above, several theoretical initiatives and lab-experiences were developed. The majority of them are focused on improving the DSG technology, because DSG pushes steam temperatures beyond 500 °C, and parasitic power consumption is reduced significantly. Moreover, the DSG installations improve the fossil backup efficiency [37].

In order to develop a new thermal energy storage system, competitive and adapted to DSG solar plants with parabolic trough technology, the DISTOR project started in February 2004, in PSA (Almeria, Spain). The DISTOR project is organized in three consecutive phases:

- Fundamentals: identification of requirements resulting from solar thermal application, characterization of PCM, and development of first physical models.
- Laboratory-scale test: Four different storage systems are manufactured and tested in the laboratory, having a power of 5–10 kW.
- A selected storage concept is connected to the Direct Solar Steam (DISS) test facility in Almeria, Spain and operated with steam provided by solar collectors.

Solar thermal systems including DSG in the absorbers require isothermal energy storage systems. One option to fulfil this requirement is the application of phase change materials (PCM) to absorb or release energy. The implementation of cost-effective storage systems requires the compensation of the low thermal heat conductivity that is characteristic for the candidate materials for PCM. Solar steam generation for power plants requires latent heat storage systems for a steam saturation temperature range between 200 and 320 °C (this range of temperatures is valid for parabolic trough technology, but not enough for central receiver plants).

Regarding efficiency, a fundamental requirement for thermal storage is the minimization of temperature differences between working fluid and storage medium. This requires isothermal storage systems for the DSG-process. An obvious solution is the application of latent heat storage materials. The selection of the

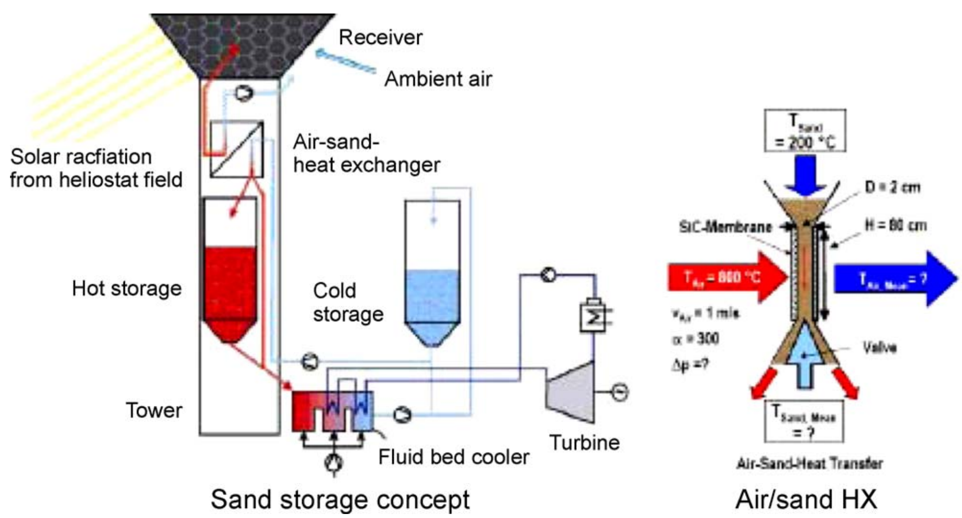

Fig. 23. Scheme of function of the fluidised bed integrated storage system [41].

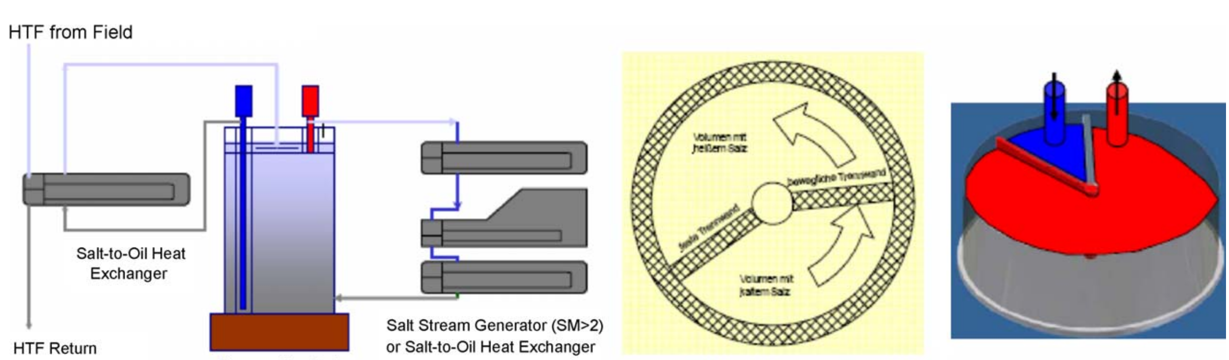

Fig. 24. Scheme of one tank movable wall concept [41].

Table 2
Advantages and disadvantages for all of thermal energy storage concepts.

System			Advantages	Disadvantages
Active storage	Direct system	Direct steam generation	- Intermediate heat transfer fluid and steam-generation exchanger is not necessary, improving the efficiency loss in steam generation.	- Increase of pipe installation cost (is necessary to work at very high pressures).
			- Overall plant configuration more simple.	- Need of auxiliary protective heating systems for start-up, maintenance and recover from frozen conditions.
			- Lower investment and O&M costs.	- Instability of the two phase flow inside the receiver tubes (procedures for filling and draining).
			- Allow the solar field operate at higher temperatures, increasing the power cycle efficiency (Reduction of LEC).	- Difficult to control the solar field under solar radiation transients.
		Two tanks	- Cold and hot HTF are stored separately.	- Very high cost of the material used as HTF and TES.
			- Low-risk approach.	- High cost of the heat exchangers and two tanks due to very large tank size requirements.
			- Possibility to raise the solar field output temperature to 450/500 °C (in trough plants), thereby increasing the Rankine cycle efficiency of the power block steam turbine to the 40% range.	- Relatively small temperature difference between the hot and cold fluid in the storage system.
			- The HTF temperature rise in the collector field can increase up to a factor of 2.5, reducing the physical size of the thermal storage system.	- Very high risk of solidification of storage fluid, due to its relatively high freeze point (that increases the M&O costs).
				- The high temperature of both tanks drives to an increase of losses in the solar field.
				- The lowest cost TES design does not correspond to the lowest cost of electricity.
	Indirect system	Two tanks	- Cold and hot HTF are stored separately.	- Very high cost of the material used as TES.
			- Low-risk approach.	- High cost of the heat exchangers and two tanks due to very large tank size requirements.
			- The HTF temperature rise in the collector field can reduce the physical size of the thermal storage system.	- Exchanger between the HTF and TES material is needed.
			- TES material flows only between hot and cold tanks, not through the parabolic troughs (decrease the risk of solidification of salts).	- Relatively small temperature difference between the hot and cold fluid in the storage system.
				- The high temperature of both tanks drives to an increase of losses in the solar field.
				- Decrease of the efficiency comparing with two tanks direct system.
		Cascaded tanks	- Higher utilization of PCM-storage capacities.	- Heavy increase of cost, due to a higher number of: storage tanks, heat transfer fluid loops and PCM.
			- More uniform outlet temperature over time.	- Further PCM need to be identified which also offer a sufficient heat of fusion and a satisfying corrosiveness.
				- Not real experiences, only simulation.
		One tank (thermocline with filler materials)	- Decrease of storage tanks cost, due to this system uses only one tank.	- Relatively high freeze point of most molten salts formulations (is necessary to maintain a minimum system temperature to avoid freezing and salt dissociation).

Table 2 (*Continued*)

System			Advantages	Disadvantages
			- Low cost of the filler materials (rocks and sand). - In cost comparisons, the thermocline system is about 35% cheaper than the two-tank storage system, due to reduction of storage volume and elimination of one tank.	- More difficult to separate the hot and cold HTF. - The high outlet temperature drives to an increase of losses in the solar field.
				- Maintaining of thermal stratification requires a controlled charging and discharging procedure, and appropriate methods or devices to avoid mixing. - Design of storage system was complex. - Thermodynamically it was an inefficient power plant. - This system is riskier with respect to the performance.
Passive storage	Concrete/ceramics	- Very low cost of thermal energy storage media, due mainly to the filler cost. - High heat transfer rates into and out of the solid medium (due to a good contact between the concrete and piping). - Facility to handling of the material. - Low degradation of heat transfer between the heat exchanger and the storage material.	- Increase of cost of heat exchanger and of engineering. - Long-term instability.	
	PCM-sensible-PCM	- Increasing of capacity storage. - Better use of PCM-storage capacities. - Reduction of costs, comparing with storage systems with only PCM as storage media. - Improve of storage ratio, comparing with systems with only sensible heat materials.	- Necessary to develop technologies to analyze this concept.	
Chemical storage (with NH_3)	- Unwanted side reactions are not possible, making solar reactors very easy to control. - The endothermic reaction takes place at temperatures well suited to solar concentrators. - Automatic phase separation of ammonia and hydrogen/nitrogen is provided, and can use a common storage tank. - There is around 100 years of industrial experience with the Harber-Bosch process.	- Laboratory-scale experiences.		

latent heat storage material depends strongly on the saturation temperature resulting from the pressure in the steam cycle. The evaporation process with an operation range of 2–30 bar requires melting temperatures between 120 and 230 °C.

Candidate materials for latent heat storage systems are salts. Although this approach has often been suggested, only limited experience is available in this temperature range. Most problems result from the low thermal conductivity of salts, particularly in the solid phase.

Two approaches are being developed by DLR to overcome these problems: one is to reduce the specific resistance for heat conduction in the PCM (external or internal arrangement), and the other to reduce the average distance for heat conduction within the storage material (Fig. 19) [38].

The first proposal consists in an internal arrangement, where the HTF flows along a vessel and through the capsules of PCM/graphite composite (Fig. 20). In this case, the vessel is pressurized, and it is possible to reach a high ratio of material encapsulation.

In this proposal, arrangement can also be external (Fig. 21), which is characterized by a low pressure storage and, on the side of production process, a low material fabrication complexity.

The higher mass specific price of graphite foil is more than balanced by low density and high thermal conductivity. The investment costs for extended heat transfer structures made of graphite foil are expected to be significantly lower than those for steel. Another significant advantage of graphite foil is its good corrosion resistivity against nitrate salts, which are used as PCM (Fig. 22). The corrosion behaviour of the storage material excludes the application of aluminium, which would otherwise be attractive due to high thermal conductivity and low density.

An experimental lab-scale of graphite foil concept was tested by SGL. The HTF of this prototype was synthetic oil, and the PCM had a melting point of 220 °C. The power output was 2 kW, and the storage unit could store about 10 kWh [39].

All these concepts can be applied in solar thermal power plants with a power range from 10 to 300 MW, and with temperature ranges between 250 and 350 °C.

In the initial phase of the DISTOR project, the application of composite material using graphite as an additional component, the integration of fins made of graphite foil, and the use of an intermediate heat transfer medium have been identified as the most promising concepts while others have been abandoned. The laboratory tests provided the basis for the identification of the concept showing the greatest potential for the implementation of a cost-effective latent heat storage system. The selected concept is being evaluated during further tests in a larger scale with steam provided by solar collectors [40]. DLR is scheduled to test different improved solutions of thermal energy storage, all of them focused on DSG power plants.

2.2.2. Innovate long term approaches using sensible heat materials

2.2.2.1. Fluidised bed storage concept. A new concept of thermal energy storage system was developed in DLR in Stuttgart: integrated receiver/storage system, using a fluidised bed storage concept. In this case, an air-to-sand heat exchanger is installed in the receiver tower in order to minimize losses. Sand is fluidised into the exchanger, in order to pass the air through it. Air reaches very high temperatures in the receiver, which means improving the efficiency and the storage rates of the plant (Fig. 23) [41].

2.2.2.2. Movable wall concept. Recent research activities carried out by DLR developed of a single tank concept with the aim to use one tank instead of two tanks concept (Fig. 24). This concept uses a mechanical separation of the cold and hot molten salt volume [41]. The main advantage expected of this concept is a heavy reduction of investment due to a fact that there is only a tank. Another advantage is the reduction of the thermal losses thanks to the fact that the hot and cold molten salts are separated only for the internal movable wall. The feasibility of the concept must be studied.

3. Summary of case studies

Every technology has a list of advantages and disadvantages. Table 2 shows, the summary list all of them.

In order to see what kind of technology is more developed and which others are under development, Table 3 shows a classification of the solar power plants in operation with storage system, according to the storage concept.

Table 4 shows a summary of the different examples of technologies, and their main characteristics.

Table 3
Summary of solar power plants in use or under construction around the world.

Storage concepts			Storage media				
			Sensible heat				Latent heat
			Liquid			Solid	
			Steam	Oil	Molten salts		
Active storage	Direct system	Direct steam generation	PS10 PS20 (u.c.)	–	–	–	–
		Two tanks	–	SEGS I (d.) SEGS II	THEMIS (d.) Solar Two (d.) Solar Tres (u.c.)	–	–
	Indirect system	One tank (thermocline)	—	SSPS DCS (PSA)	Solar One (d.)	–	–
		Two tanks	–	–	SSPS CESA I (PSA) SSPS CERS (PSA) Andasol I Andasol II (u.c.) Extresol I (u.c.)		
		Cascaded tanks	–	–	–	–	LUZ proposal for Solar Plant
Passive storage	Concrete/ ceramics	–	–	–	SSPS LS3 (PSA)	–	
	PCM-concrete -PCM	–	–	–	DLR-ZSW proposal SGL proposal		

u.c.—under construction.
d.—dismantled.

Table 4
Summary of different technologies and materials used in the solar power plants with storage systems existing in the world.

Plant configuration	Storage concept	Experiences/projects	Year	Thermal capacity (MWh_{th})	Total capacity (MWe)	Operating range temperature (°)	Annual capacity factor	HTF	TES media
Trough plant	Passive system	LS3-SSPS-PSA, Spain	2004	0.48	n.a.	n.a.	n.a.	Mineral Oil	High-temperature concrete vs. Catastable ceramics
	Active Indirect system (Two-Tanks)	ANDASOL I-SENER/Cobra, Guadix, Spain	2008	1010	n.a.	384–291	14.70%	Steam	Molten salts (60% $NaNO_3$ + 40% KNO_3)
				1010	50	560–260			
				880	n.a.	382–296			
				(6–12 h)		384–292			
	Active Indirect system (Two-Tanks)	ANDASOL II-SENER/Cobra, Guadix, Spain	2009	n.a.	n.a.	n.a.	n.a.	Steam	Molten salts
	Active Indirect system (Two-Tanks)	EXTRESOL I-SENER/Cobra	Project (scheduled in 2010)	(12 h)	50	n.a.	n.a.	Synthetic Oil	Molten salts
	n.a.	SOLANA, Phoenix, AR, USA	Project (scheduled in 2011)	n.a.	280	n.a.	n.a.	n.a.	n.a.
	Active Direct system (Two-Tanks)	SEGS I, Dagget, CA, USA	1984–2001	115	14	307–n.a.	n.a.	Mineral Oil (CALORIA)	Mineral Oil (CALORIA)
				120		n.a.			
				120 (3 h)		307–240			
	Active Direct system (Two-Tanks)	SEGS II, Dagget, CA, USA	1985	n.a.	30	316–n.a.	n.a.	Mineral Oil (ESSO 500)	Mineral Oil (ESSO 500)
	Active Direct system (Two-Tanks)	SSPS DCS, PSA Spain	1981	0.5	–	180–290	n.a.	Mineral Oil (Santotherm 55)	Mineral Oil (Santotherm 55)
				–	1.2				
	n.a.	HELIOS I-Abengoa, Ciudad Real	Project	n.a.	50	n.a.	n.a.	n.a.	n.a.
	n.a.	HELIOS II-Abengoa, Ciudad Real	Project	n.a.	50	n.a.	n.a.	n.a.	n.a.
Central receiver plant	Active Indirect system (Single Tank)	Solar One, Barstow, CA, USA	1982–1988	182	10	304–224	16%	Steam	Mineral oil + sand + rocks
	Active Direct system (Two-Tanks)	Solar Two, Barstow, CA, USA	1996–1999	105	10	n.a.	19%	Molten salt	Molten salt
			1995–1999	105	10	565–275		Molten nitrate (40% KNO_3 + 60% $NaNO_3$)	Molten nitrate
				114 (3 h)	n.a.	565–290			
	Active Indirect system (Two-Tanks)	CESA I-PSA, Spain	1983	7	1.2	340–220	n.a.	Steam	Molten salts
			1982	n.a.	1	n.a.		Steam	Molten salts (nitrate)
				12		520		Steam (100 bar)	Molten salts
	Active Indirect system (Two-Tanks)	CERS-SSPS PSA, Spain	1981	2.7	0.5	n.a.	n.a.	Molten salt (liquid sodium)	Molten salt (sodium)
	Active Direct system (Two-Tanks)	THEMIS, Targasonne, France	1982 1984	40	2.5	450–250	n.a.	Molten salt (High technology)	Molten salt (High technology)
	Active Direct system (Direct steam generation)	PS10-Abengoa, Sevilla, Spain	2007	15 (50 min)	11	n.a.	n.a.	Steam	Steam–ceramic
	Active Direct system (Direct steam generation)	PS20-Abengoa, Sevilla, Spain	2007	n.a.	20	n.a.	n.a.	Steam	Steam–ceramic
	Active Direct system (Two-Tanks)	SOLAR TRES-PSA, Spain (SENER)	2002–2007	588 (16 h)	17	565–288	13.81%	Molten salts ($NaNO_3$ + KNO_3)	Molten salts ($NaNO_3$ + KNO_3)
					15	565–290			
PCM	Passive system (Cascade PCM storage)	LUZ proposal for Solar Plant	1990	875	–	345–295	n.a.	Synthetic oil	$MgCl_2$/KCl/NaCl; KOH; KNO_3; KNO_3/KCl; $NaNO_3$
	Passive system (PCM-sensible-PCM)	DLR-ZSW proposal for Solar Plant	1993	n.a.	n.a.	n.a.	n.a.	Synthetic oil	$NaNO_3$/Concrete/NaOH/NaCl
Solar dish	Ammonia Dissociation/Synthesis	Theoretical and laboratory-scale experiences	1998	0.015	–	750 (20 MPa)		Ammonia	Ammonia
				1			13.94	Ammonia	Ammonia
				10			19.14	Ammonia	Ammonia
	Metal Oxide/Metal (SnO_x/Sn)	Theoretical	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

4. Conclusions

This paper has presented an updated review of the main experiences of high-temperature storage systems in concentrated solar power plants in the world. The following conclusions can be drawn:

- Several options are applied as the heat transfer fluid in the solar field, including steam, mineral oils, molten salts, and ammonia. Most of the new plants built recently, all of them in Spain, are using steam as the heat transfer fluid. The main advantages of direct steam generation are that the overall plant configuration is more simple and it allows the solar field to operate at higher temperatures compared to oil.
- The most commonly used thermal storage media for this application in the eighties were mineral oil and molten salts (a mixture of $NaNO_3$ and KNO_3). In the most recent solar power plants in Spain the options selected have been either molten salts, or steam in combination with solid storage. High-temperature concrete and castable ceramics have been also recently investigated as a cost-effective alternative in a through pilot plant in Spain. Other options, such as a combination of PCM with different melting points or ammonia have been proposed on paper as alternatives.
- Both active and passive storage concepts were used in solar power plants experiences in the eighties, as well as in the new solar power plants built after 2000.
- For the trough power plants built in the eighties the selected thermal storage system configuration was the active direct system with mineral oil as both the HTF and the storage media. In the most recent experiences or projects the active indirect storage system is preferred, using molten salts as the storage media and either steam or synthetic oil as the HTF. In one experimental small plant passive storage, using mineral oil as HTF and concrete or ceramics as storage media, was investigated.
- In the case of central receiver solar power plants the early experiences in the eighties in California and France used an active direct two tanks system with molten salts, whereas the experiences in Spain preferred the indirect two-tank storage system, with steam as the HTF and molten salts as storage medium. Regarding the most recent central receiver power plants, in two cases in Spain a passive storage single tank system using steam as HTF and a combination of steam and ceramics for thermal storage was selected, and in a third case study also in Spain an active direct storage system with molten salts was applied.
- Other innovative concepts have been investigated on paper to improve the performance of thermal storage in solar power plants and other industrial high-temperature applications. This ideas include the combination of sensible and latent heat storage using PCM; fluidised bed storage concepts using sand for storage and air as HTF; chemical storage using ammonia formation reaction in a parabolidal dish concentrator, and a movable wall concept (this concept uses a mechanical separation of the cold and hot molten salt volume).

Acknowledgments

This work was partially funded by ENE2005-08256-C02-01/ALT, ENE2005-08256-C02-02/CON, and 2005-SGR-00324. The authors would like to acknowledge the participation of Abengoa Solar NT.

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